Probing extended scalar sectors in multi-Higgs channels : Prospects at Future proton-proton Colliders

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Owing to its unique role in regularizing the standard model of particle physics (SM) and giving mass to vector bosons and fermions, the Higgs sector is an ideal place to look for physics beyond the standard model (BSM). Many BSM models, in particular, feature extensions of the scalar sector with additional fields, resulting in a rich phenomenology with additional scalar bosons. Examples are the Higgs sector of the next-to-minimal supersymmetric SM (NMSSM) [1,2], the extension of the SM scalar sector with two real scalar singlets [3] or models with warped extra dimensions [4].

At a pp collider, these models can manifest with a characteristic signature of resonant production of two or more scalar bosons. Denoting with H the 125 GeV Higgs boson and as H' and h the two additional bosons, the production of the new resonance H' that decays to other bosons (H' → HH, H' → hh, H' → Hh) can manifest with a branching fraction that is dominant for many models over a broad part of their parameter space. While we usually regard H' as the heaviest state, the mass hierarchy of H and h can vary depending on the model considered and its parameters. In particular, if $m_h > 2m_H$, cascade processes can arise where h subsequently decays to SM Higgs boson pairs (h→ HH), resulting in spectacular three- and four-Higgs boson signatures.

In this field, ATLAS and CMS solely concentrated on di-Higgs searches via resonant production (H' → HH). The measurements done at LHC allowed to put limits on new particles such as the spin-0 radion and the spin-2 first Kaluza-Klein excitation of the graviton, which have sizable branching fractions to HH. Studies for HL-LHC indicate that exclusion limits can be set up to masses of ~3 TeV [5]: investigating these channels at higher energy proton-proton (pp) colliders beyond the LHC will allow to probe a much wider mass range.

Searches for resonant di-Higgs production can shed light on the generation of the baryon asymmetry of the Universe. The additional BSM bosonic degrees of freedom could lead to a strongly first-order electroweak phase transition, allowing to generate the matter-antimatter asymmetry. While the HL-LHC will only be able to explore a limited portion of the corresponding region of parameter space, preliminary studies indicated that significant progress could be made at, e.g., the FCC-hh (100 TeV) with 30/ab of data [6].

Together with the investigation of di-Higgs resonant production, the work proposed in this project addresses also asymmetric and cascade decays, which are essentially unexplored and may have been so far undetected without a dedicated search. There is a large potential for discovery in these signatures at present colliders and in future high-luminosity and high-energy pp facilities.

Building on the results of previous phenomenological studies on similar signatures [7,8], this project aims at studying the prospects for discovery of extended scalar sectors in the multi-scalar boson topologies described above. Benefiting on the largest branching fraction, decays of the scalar bosons to b quarks are studied in four (H' → HH → bb bb and H' → Hh → bb bb) and six (H' → Hh, H →bb, h→ HH → bbbb) b jets final states. Prospects for the sensitivity will be studied for future pp colliders at a center-of-mass energy of 14 TeV (HL-LHC), 27 TeV (HE-LHC), and 100 TeV (FCC-hh).

Using a fast detector simulation of the signal and of the multijet background processes, we propose to develop a dedicated analysis strategy that retains sensitivity for a broad range of m_h and $m_{H'}$. The large number of final state objects and the rich kinematic information provide a unique environment to test the application of advanced machine learning methods for jet selection and paring and for background rejection. These studies can address the question of the expected sensitivity to these types of signatures at present and future colliders and pave the way to the development of a dedicated LHC search.

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JHEP 02 (2020) 002 10.1007/JHEP02(2020)002